REPAIR OF LANDSLIDES

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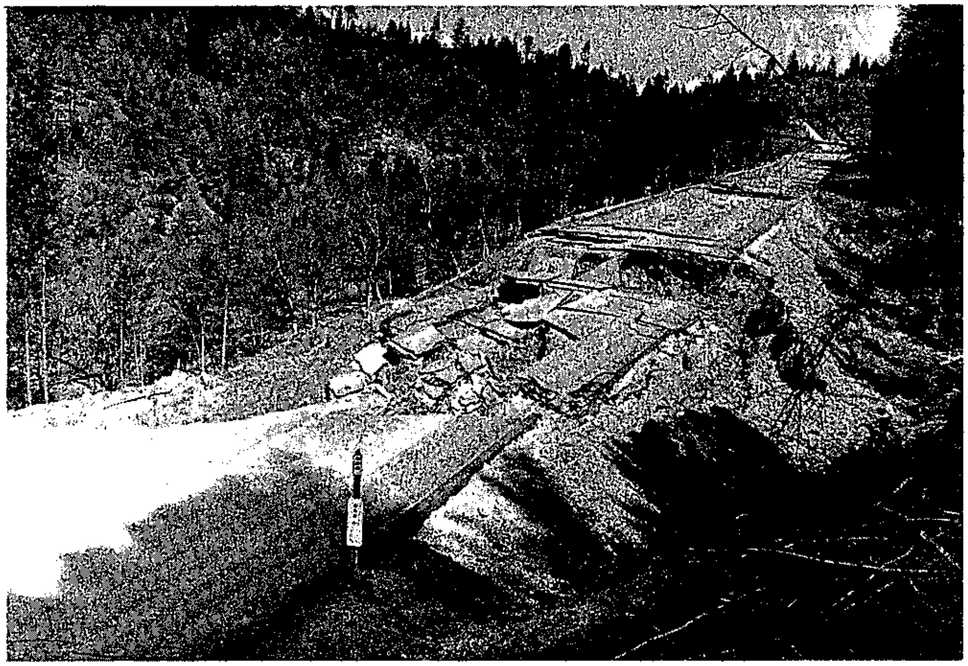

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Introduction

The repair of landslides cannot be separated completely from the detection, investigation, causes, prevention and economics involved in landslides. Other presentations at this meeting have discussed some of these facets in connection with landslides. It is not my intention to infringe upon their discussions, but some discussion on my part is desirable in order to adequately discuss the subject "repair of landslides." Landslides have been the subject of many studies and publications. An excellent reference on the subject is HRB, Special Report 29, Landslides and Engineering Practice (1).

I would like to emphasize that one of the most important phases of the repair of landslides is adequate investigation. Depending upon the conditions involved, investigations may take many forms. They may be meager or extensive, and may or may not completely determine all of the causes or elements that contribute to a landslide. Some of the more common means of investigation are field reconnaissance, geologic mapping, aerial photo interpretation, geophysical studies, borings, testing, ground water studies and mathematical analysis. It should be emphasized that an important aspect of all of these methods of investigation

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is the experience and the competence to properly evaluate the information obtained. Broad knowledge in geology, soil mechanics, civil engineering, construction practices, and economics are important. The concept has frequently developed that professional engineering geology, soil mechanics, and civil engineering are somehow in competition in the repair of landslides. I am not in accord with this line of thinking. Each of these professions has its place and can make valuable contributions. Their activities overlap and for the most part are inseparable.

The repair of some landslides may necessitate an investigation that involves essentially all of the above types of studies; whereas other landslide investigations might involve only one of these procedures and then in only a cursory manner. However, most frequently the investigation will consist of a combination of two or more of the above techniques. An example of a simpler type of investigation might be a small landslide where a field reconnaissance would indicate that the landslide could be avoided by a simple relocation, or could economically be removed. In this case little or no additional investigation might be necessary. Examples of landslides can be cited where conditions are so complex, the landslides are so extensive in scope, and costs are so large that even the most comprehensive investigation that is economically reasonable would still leave something to be desired.

Fundamentally, a landslide results when the forces tending to produce sliding exceed the forces tending to prevent sliding. Primarily the forces that produce sliding are components of gravitational forces. The weight of the rock, soil and water produce forces that act in the direction that the slide tends to move. In the repair of landslides it is possible to reduce the forces tending to produce failure by removal of load at the proper locations. It is also possible to reduce the activating forces by subdrainage and thus eliminate hydrostatic pressure and diminish the weight of the soil mass by reducing moisture content. The forces tending to prevent sliding are primarily a result of strength within the mass combined with components of gravitational forces that act in the proper direction. It should be noted that in most cases the greatest stabilizing effect of subdrainage is due to increasing the shear strength of the soil rather than by reduction of the motivating forces.

There are many ways in which the forces resisting slide movement can be increased. These include subdrainage, thus, increasing the shearing strength as mentioned above; construction of buttresses or retaining type structures; and removal or elimination of low strength material. One method of repair of landslides or rather elimination of a landslide problem is to relocate the road, structure or facility to a location that will be unaffected by the landslide (Fig. 1). Although this

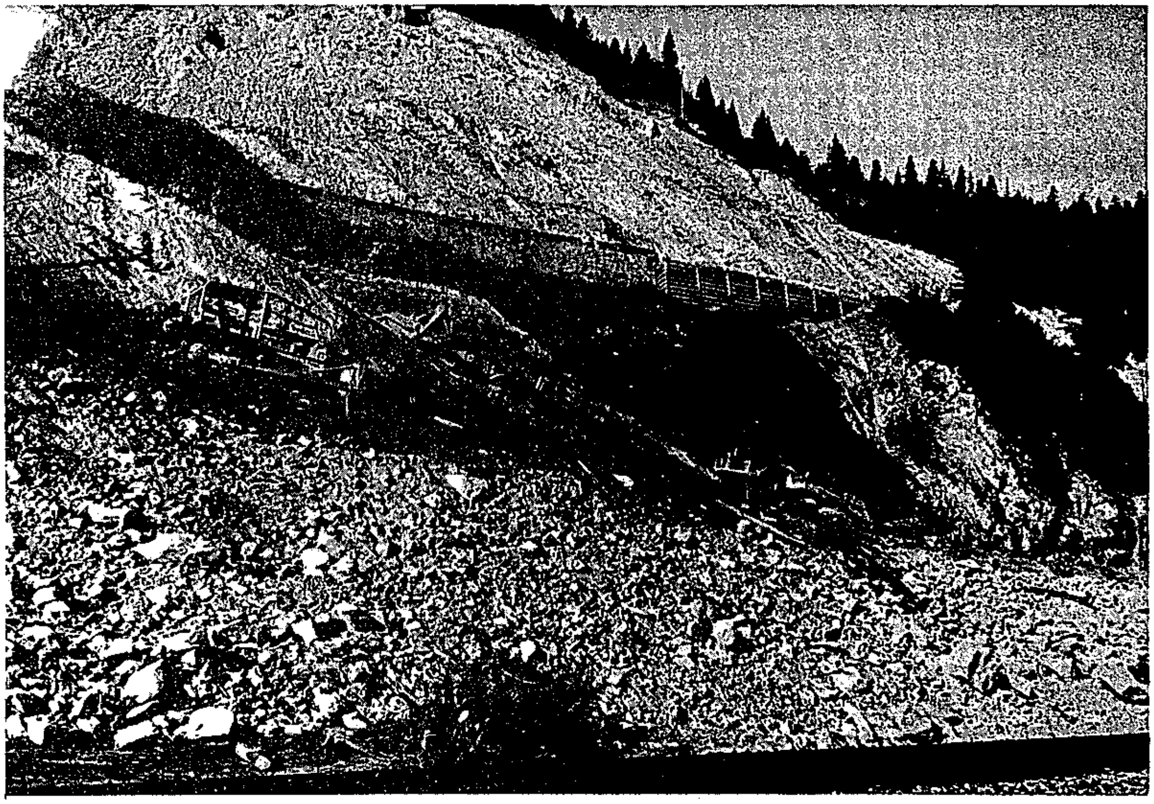


Fig. 1 - Avoiding landslide by relocating railroad and highway - south of Dunsmuir.

method should be fairly obvious and should generally be considered it is frequently overlooked. Use of this technique may not only eliminate the cost of repair of the landslide, it might eliminate most or all of the cost of the investigation.

Landslides can be classified by several different means. One fairly simple type of classification would be in two categories, man-made and natural landslides (Figs. 2 & 3). Natural

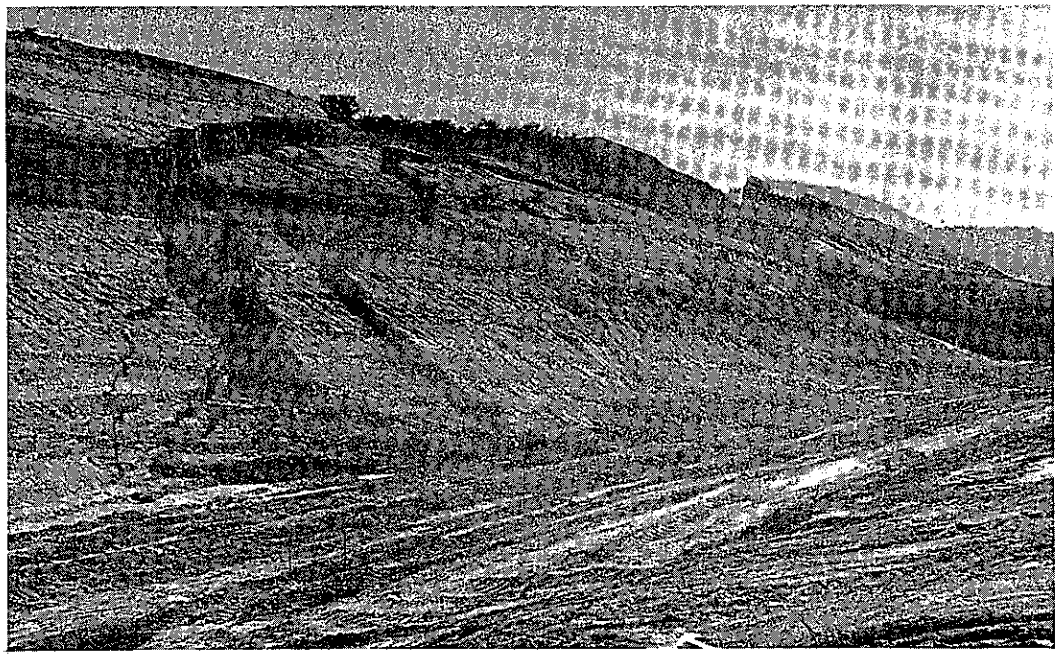


Fig. 2 - Man-made landslide - caused by highway construction.

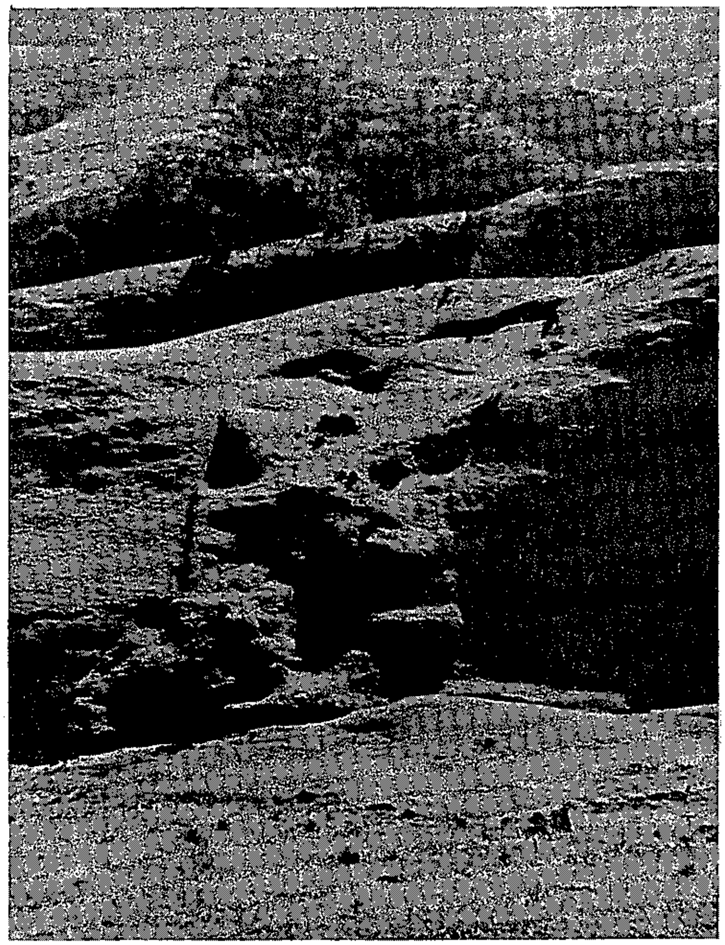


Fig. 3 - Natural landslide - a common sight on the California landscape.

landslides are quite prevalent in California, particularly in the northern and coastal regions where rainfall is high and geologic or soil conditions are complex and poor. Man-made landslides are the result of construction of engineering facilities in areas where soils or geologic conditions are similar or better than conditions where natural landslides already exist. We, in highways, frequently classify landslides as involving cuts or embankments. These landslides are man-made. We frequently make cuts or construct embankments in areas where natural landslides exist. Landslides in either cuts or embankments may be very complex and expensive to repair; however, we generally find that those involving embankments constitute our most serious problems. This generally evolves from the fact that they constitute a serious problem as far as handling traffic; whereas a landslide in a cut might be contained on the shoulder of the roadway or require the restricting of traffic to a portion of the roadway. In our experience the two most common causes of landslides are subsurface water and poor soil conditions. Frequently these two causes operate jointly.

One of the more commonly used techniques for repair of landslides is excavation or slope flattening. This method is most commonly used where cut slope failures are involved, better quality material exists above the head of the slide, and right of way or economic considerations permit the procurement of additional right of way. This procedure entails essentially removal of driving force at the head of the slide. Some precautions in the use of this procedure are in order. The excavation may induce further sliding above. It is also important to be sure that removal of the material will indeed improve the stability and not worsen conditions.

Another common means of repair of landslides is by drainage. Repair of landslides by drainage can be placed in two categories, surface and subsurface. In our experience by far the most important of these is subsurface drainage; however, surface drainage should certainly not be overlooked in these repairs. Lack of provision for surface drainage is seldom, if ever, the sole cause of a landslide, but more frequently contributes to an already bad situation and aggravates or triggers a landslide.

Subsurface drainage contribures to the repair of landslides in two ways; first, removal of subsurface water generally results in a reduction in weight and hence, in a reduction in driving forces, but its more important contribution is by an increase in the shearing strength of the soil. Removal of subsurface water may be accomplished by the use of drainage blankets, stabilization trenches, horizontal drains, tunnels, relief wells, galleries, and other means. We have made extensive use in California of stabilization trenches and horizontal drains. Use of some of the other means are not nearly so extensive, but they are not at all uncommon in our practice.

Excavation

Excavation as a means of repairing landslides may take many forms. It may consist of total removal, partial removal, removal of material at the head of the slide, slope flattening, benching, in rare cases removal of material at the toe of the landslide, or a combination of various excavation techniques.

Total excavation is most commonly used on small slides, situations where right of way for removal and disposal is comparatively cheap, or situations where removal can be expeditiously executed, and it is imperative that the engineering facility to be protected must be kept in operation (Fig. 4). If a landslide involving an embankment foundation failure has occurred, it may be necessary to remove the slide material in order to start corrective action (Fig. 5). This is particularly true if extensive groundwater correction is necessary or if the strength of the slide mass has been drastically reduced. Total removal may be expensive, particularly if the slide is large, disposal is a problem, or working conditions are tight (Fig. 6). Care or consideration may be necessary to insure that further sliding or instability does not result from total removal.

Partial removal of landslides is frequently used as a means of improving stability in landslides. In other words, it may be possible to remove portions of the sliding mass, leave portions in place, and actually improve the stability. These situations will require careful analyses and are almost wholly dependent upon the geometrics of the landslide and adjacent terrain and soil conditions. The next three excavation procedures may constitute partial removal.

In many cases it may be possible to improve the stability of a landslide by removing material at the head of a slide (Fig. 7). This removal may eliminate sufficient driving force

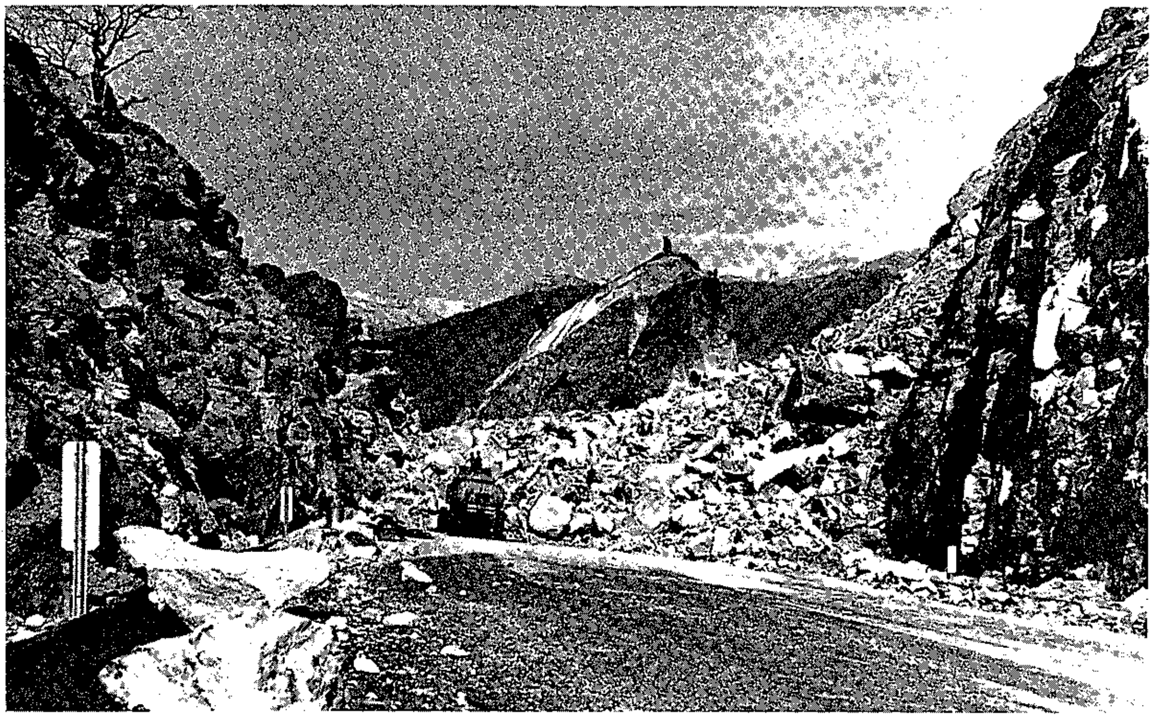


Fig. 4 - Protecting engineering facility (highway) by total removal of landslide - east of Visalia.

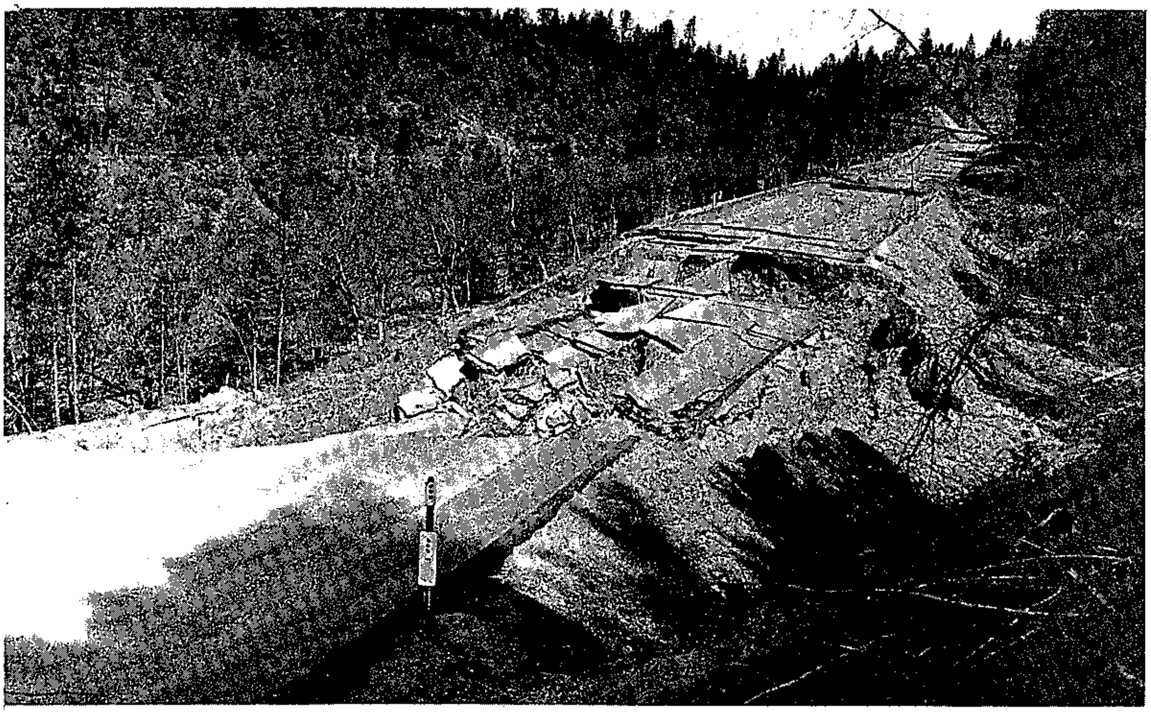


Fig. 5 - Loss of Highway by landslide requiring complete removal before corrective action - Trinity County.

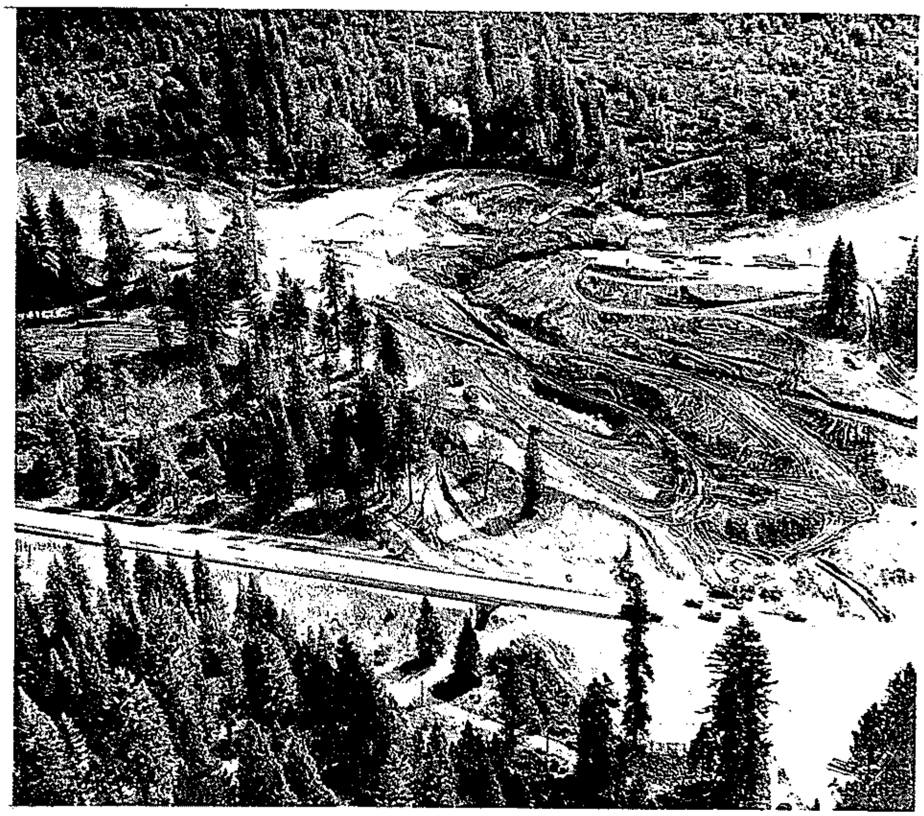


Fig. 6 - Repairing damage of landslide by complete removal - Highway 80, Whitmore Grade.

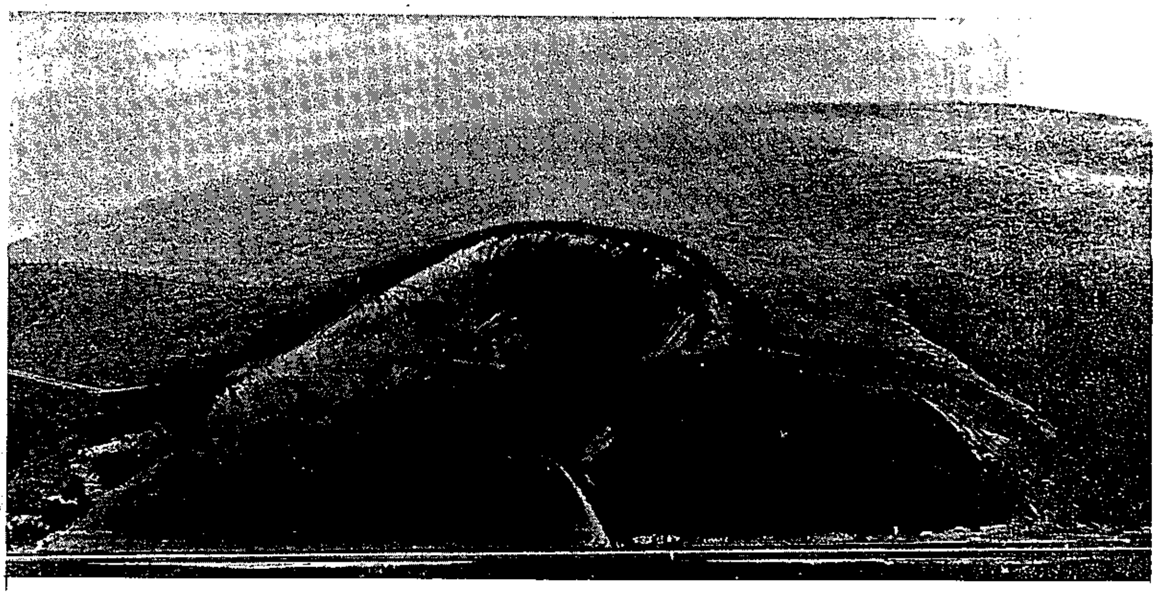
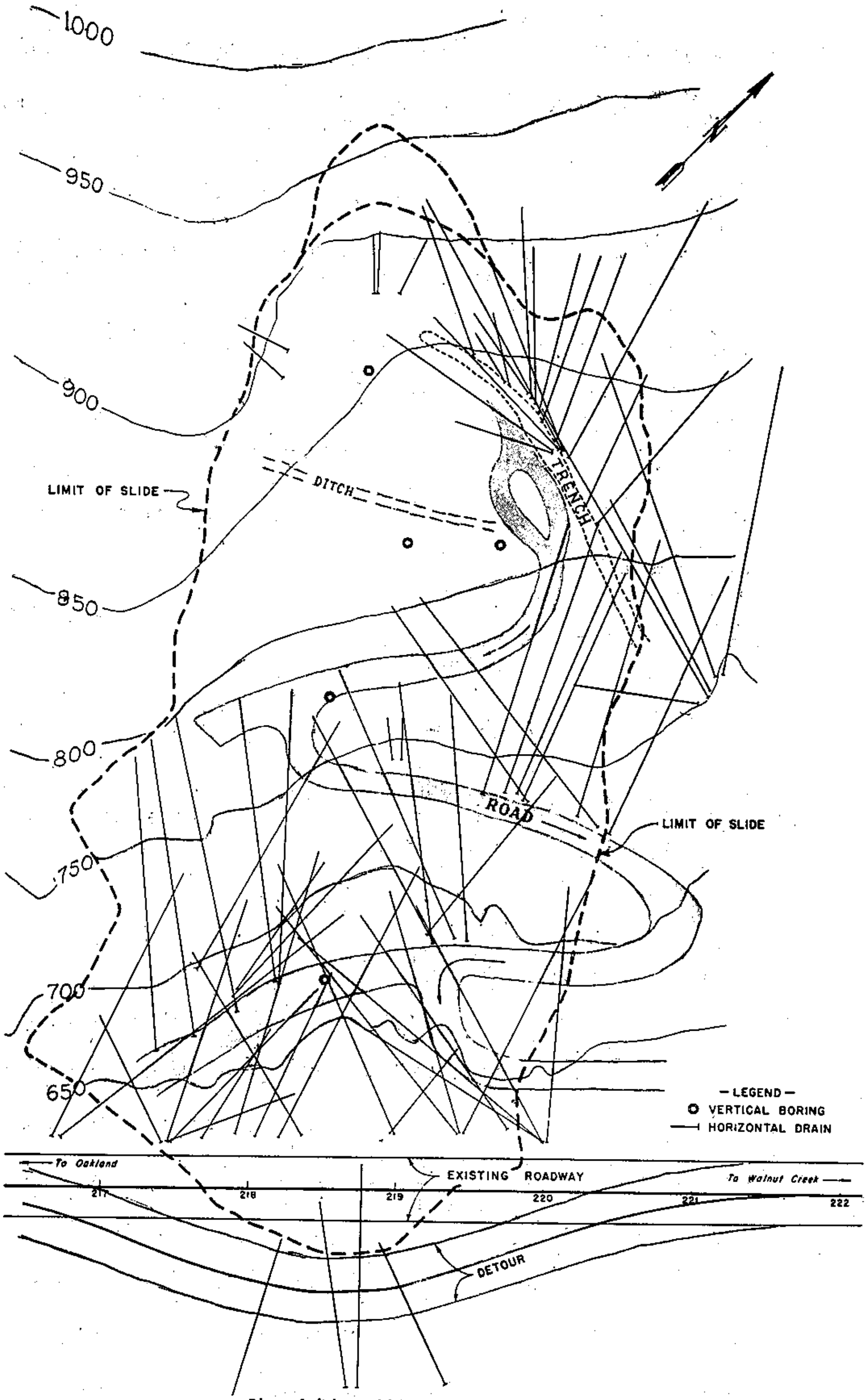


Fig. 7 - Removing material at head of landslide to improve stability - Highway 50 near Livermore.

to bring the sliding mass to a condition of equilibrium. This removal might be wholly within the slide mass but more commonly would involve some excavation from above the slide. This type of excavation will usually result in a steep cut slope in the upper part of the slide or above the slide, a flatter slope in a lower portion of the slide that will consist of slide mass, and a variable condition nearer the toe of the slide. (Figs. 8, 9 & 10). Removal at the head of the slide is most applicable if the movement has not resulted in severe or total loss of strength in the slide mass or where the terrain is progressively flatter above the landslide. In this type of excavation care is necessary to guard against forcing the landslide headward and in reality not improve the overall stability. Under the conditions described above the treatment necessary at the toe of the slide will be dependent upon the nature and condition of the slide and the situation at the toe. If an engineering facility exists at the toe of the slide and movement has not been severe no further correction may be necessary. On the other hand, if movement has been severe, reconstruction and further corrective measures may be necessary. It is sometimes possible to use an earth buttress or restraining structure at the toe of a landslide in combination with removal at the head. This procedure would be most applicable where movement has not been severe and where an engineering facility is located in the middle portion of the landslide. It is frequently possible, by grade change or relocation, to utilize the area at the base of the steepened portion below the head of the slide for a highway, railroad, or other facilities. There are, of course, some risks involved.

Fig. 8 - Orinda Slide showing its magnitude - State Highway No. 24 in foreground.

Fig. 9 - Orinda Slide after completion of repair work.



Plan of slide and horizontal drainage system

Fig. 10 - Orinda Slide plan view graphically illustrating repair treatment.

A common method of repairing landslides is to simply flatten the overall slope (Fig. 11). This method is particularly

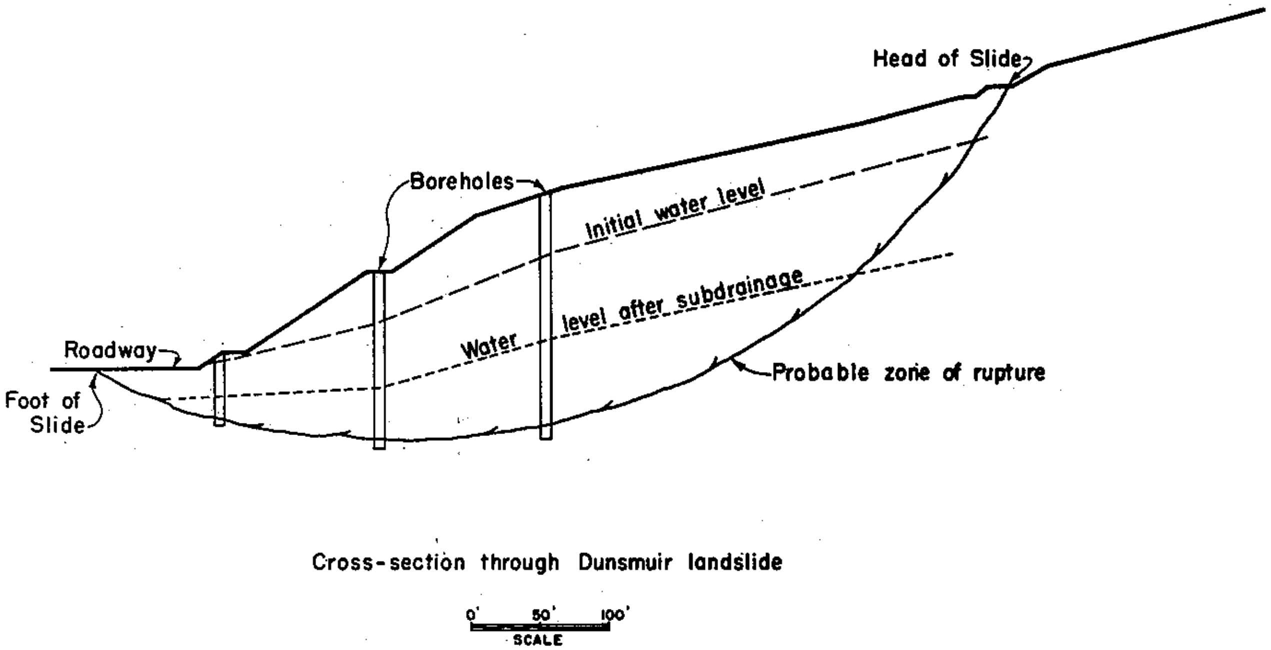


Fig. 11 - Graphic illustration of slope flattening, Dunsmuir Slide.

applicable if the landslide is the result of excavation on a slope steeper than an unfavorable bedding plane or zone of weakness. Flattening the slope to correspond to the zone of weakness may result in a stable condition. This may not result in removal of all of the slide mass. A word of precaution is advisable. Due to severe weathering or fracturing some materials may be little or no stronger across bedding planes or joints than they are along these features. In order for overall slope flattening to be effective it may be expensive.

It might result in more excavation than total removal of a slide and still leave some of the slide mass in place. It would generally result in a flatter slope above the landslide than would be characteristic of removal at the head of a landslide. This procedure may, in many situations, be similar to partial removal.

Benching as a means of landslide repair or prevention may be a part of nearly any of the excavation means previously described. However, benching may affect the procedures. It is common practice when excavating material at the head of a landslide to provide a bench or flatter slope immediately below the steeper slope at the top (Figs. 8 & 9). Since the maximum safe slope height for most material is a function of the strength of the material, it follows that an economical slope may consist of the steepest reasonable slope between benches and the overall slope as steep as possible (Fig. 12). This would not only be true for repair of landslides, it would be true for the design of safe slopes under other conditions. In sedimentary materials it is common practice to use benched cuts with slopes steeper than the adverse bedding planes and accept the risks involved. Benches tend to intensify distress between benches and reduce the risk of an overall failure or mass landslide. Benches also play an important part in landslide correction where surface or subsurface drainage is used (Fig. 13). This will be described later.

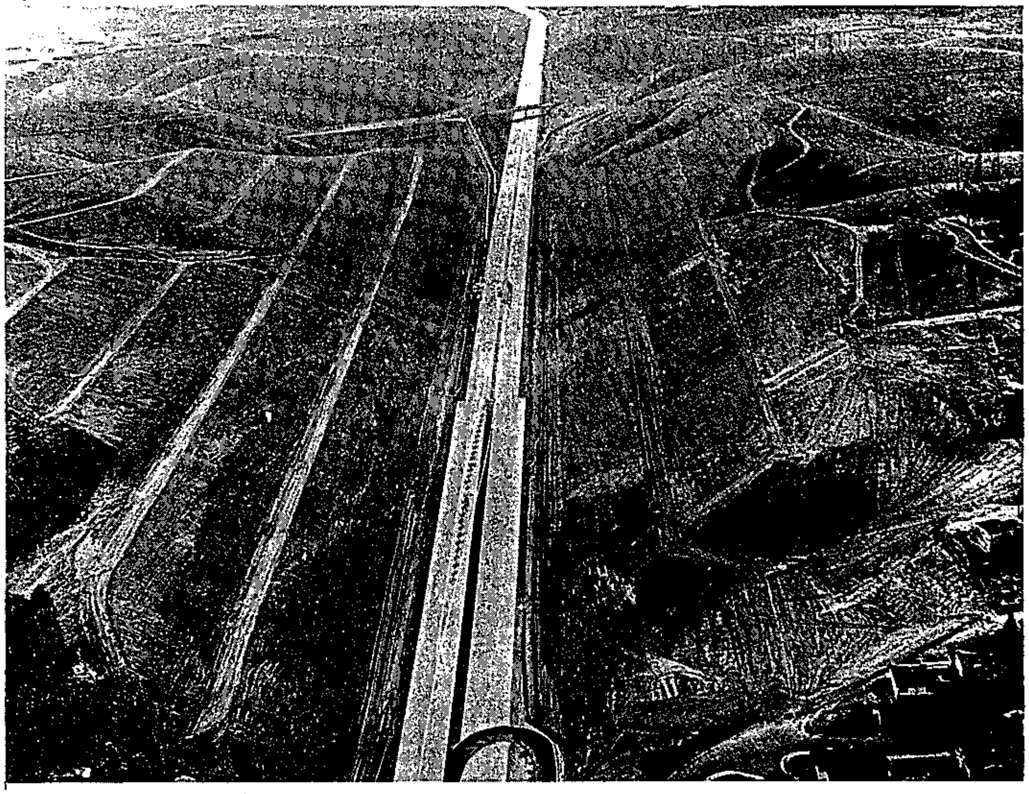


Fig. 12 - Benching and slope flattening for landslide repair.

It is sometimes possible to improve the stability of a landslide by removing material at the toe. This procedure might be placed in two categories. Small portions of material may be removed in stages at the toe and replaced with material with higher strength or a restraining structure might be added (Fig. 14). Excavation would result in a temporary reduction in stability, but if this temporary condition could be overcome stability would be improved as the procedure is continued. Material is sometimes removed from just above the toe of a landslide to cause the toe to be moved upward or inward to the

Fig. 13 - Benching and subsurface drainage combination for landslide correction, Lookout Point - Orick.

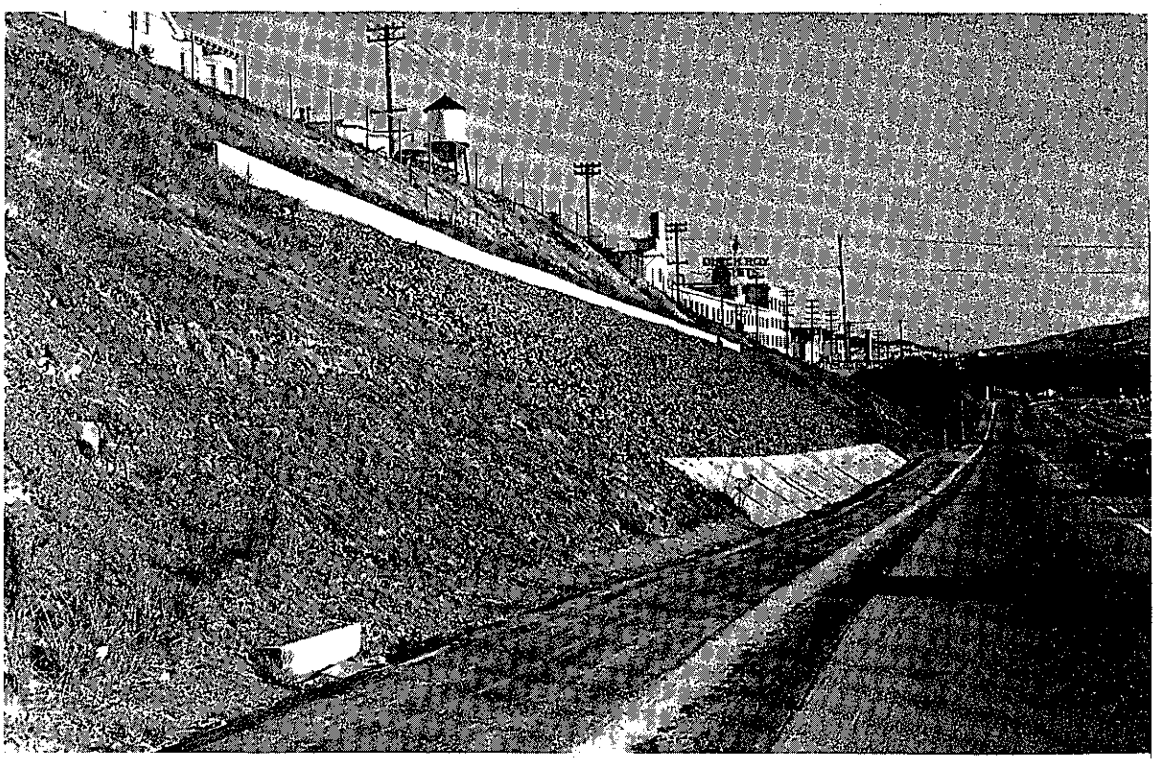


Fig. 14 - Improving landslide stability by removing slide material at toe and replacing with higher quality material and a retaining wall, Kansas Street, San Francisco.

weakened area. This might protect an engineering facility if it were located below or outward from the new toe of the landslide. This procedure will not improve the stability of the landslide, and in most cases will worsen the situation, but it may protect the engineering facility involved. There are some risks that it may not be effective in protecting the engineering facilities. It may be necessary to periodically remove material at the new toe and hence maintenance costs may be increased.

Very frequently combinations or modifications of the above excavation procedures are used. These procedures will also frequently be used in combination with subsurface drainage procedures (Figs. 15 & 16). It should be emphasized that the selection of excavation procedures should be preceded by adequate investigation and an appropriate analysis of the engineering and economic factors involved. It is well to note that many landslides may not be readily susceptible to rigorous mathematical stability analyses using strength values based on laboratory tests. This does not eliminate or seriously reduce the usefulness of these stability analyses. The laboratory tests may provide a basis for estimating the available strength when used with judgment and experience. It is possible to calculate the available strength on many landslides by the use of stability analyses if the geometrics of the landslide are fairly well determined. Stability analyses using reasonable estimates of strengths or laboratory strengths provide an excellent means of comparing various methods of landslide correction.

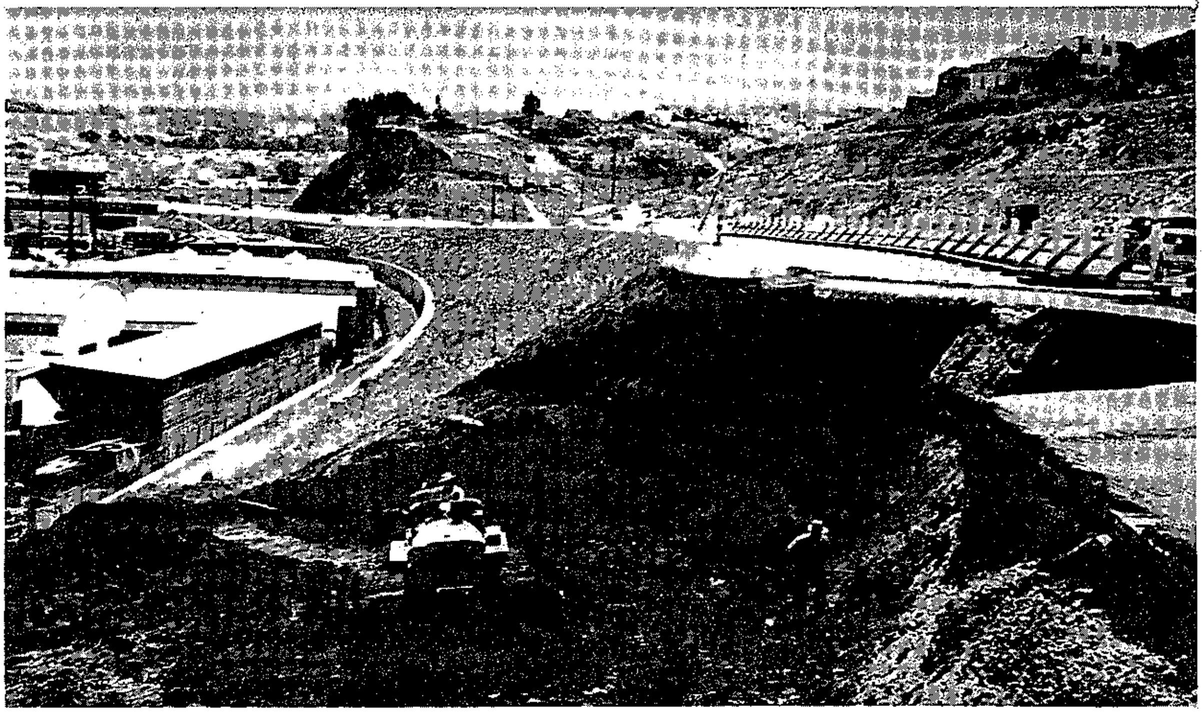


Fig. 15 - Bayshore slipout near Army Street showing adjacent industrial facilities in jeopardy - San Francisco.

Fig. 16 - Bayshore slipout after repair by buttressing and subsurface drainage.

Drainage

The comments on drainage will be confined almost exclusively to subsurface drainage. This is not to imply that surface drainage is not important. It would logically be presumed that adequate surface drainage would be provided if it would materially affect the stability of an engineering facility. The necessity for providing this drainage is even more imperative if a landslide is involved. Usually surface drainage would not be the sole cause of a landslide but percolation of surface water can certainly be a contributing factor in an existing or incipient landslide.

In our experience in California highways groundwater is probably the most extensive contributing factor to landslides. This is especially true of landslides involving embankments. Hence, it follows that efforts for subsurface drainage should be fruitful. These drainage methods are frequently combined with other methods of landslide correction.

One of the very common methods of treatment of landslides is the provision for drainage blankets or layers of permeable material. This is a far more common practice in prevention of landslides than it is in actual repair of landslides, nevertheless it is frequently used for repair purposes. Landslides may occur when embankments are constructed in sloping terrain if there are underlying strata of wet poor quality or water bearing material. Due to compression as a result of load, the permeability of the material is reduced, hydrostatic pressures are increased and more material becomes saturated and weakened as the water table rises (Fig. 5). Frequently layers of poor quality soil or slide material are removed and if groundwater is a problem the area is blanketed with permeable material and then embankment constructed over the area where the slide has occurred (Fig. 17). Hence this type of correction is far more common where fills are involved than would be the case in cut slopes. This procedure provides two benefits. First, it replaces the poor quality material or material that has been weakened due to sliding and at the same time provides material with the necessary drainage characteristics to remove groundwater from the area. This procedure has widest application in the repair of landslides where the poor quality material or area to be treated is relatively shallow. The lateral area may be of little or no concern since stripping is a fairly economical operation particularly if there are no problems in disposal of the waste material. A system of perforated pipe should be provided in the stripped area to actually remove the groundwater from the area. Our experience has been that it is generally poor practice to provide a blanket or layer of permeable material and then not go to the additional expense of providing outlets in the form of perforated pipes.

Another common method of landslide correction that we use is the installation of stabilization trenches (Fig. 18). Stabilization trenches in reality are a modification of the stripping or sand blanket procedure. They are frequently used when the depth to be stripped is prohibitive or where the area is such that it would not be practical to remove the large

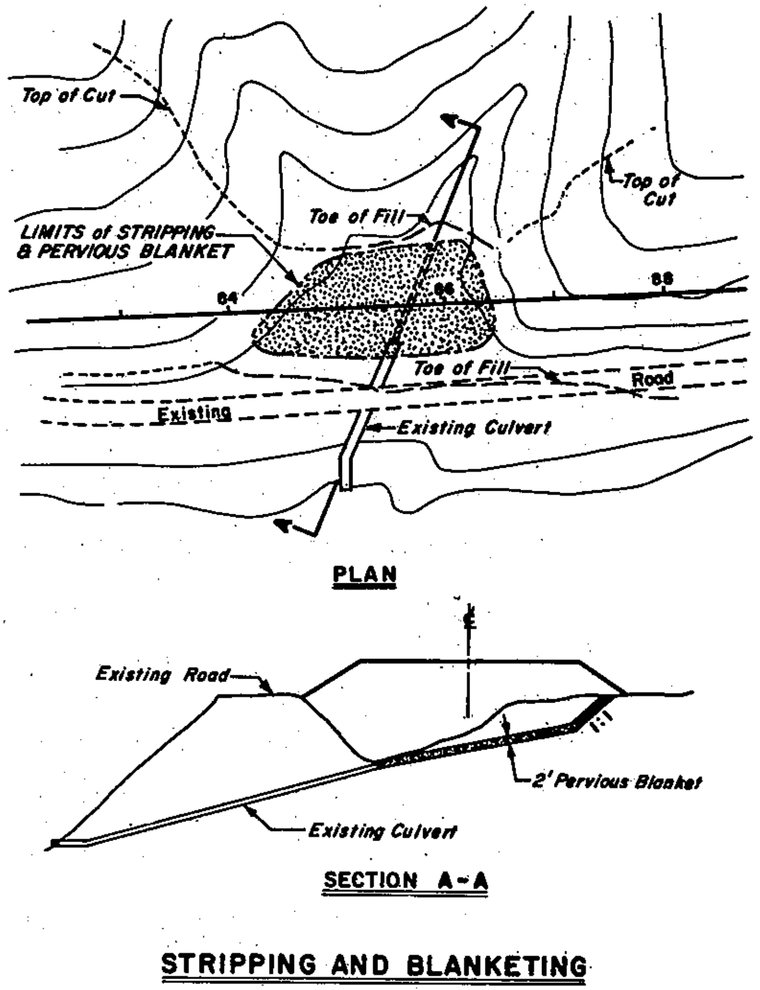


Fig. 17 - Plan and section of slide repair by stripping and blanketing with pervious material.

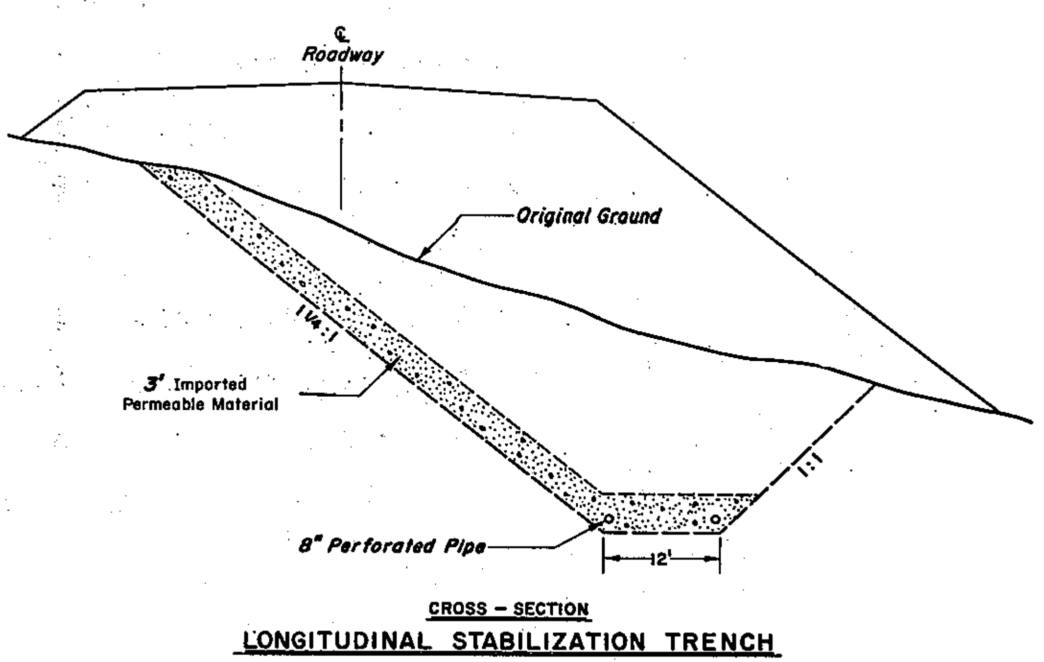


Fig. 18 - Graphic illustrations of slide correction by construction of stabilization trenches.

quantities of material. The trenches may be either transverse or longitudinal with reference to centerline. They should be oriented in relation to the needs and not controlled by the alignment of the road. They usually consist of fairly deep trenches that are constructed with normal mobile equipment. They are constructed with bottom widths in the order of 12 and 15 feet. The side slopes and end slopes are as steep as the soil conditions will permit. Since these slopes are temporary they may be steeper than would be permissible for a permanent slope. Bottoms of these trenches should be sufficiently deep to be fairly well keyed into good quality material below the strata of poor quality material (Fig. 19). The bottoms and sides of these trenches are blanketed with a 3 or 4-foot layer of permeable material (Fig. 20). An outlet, usually an extension of the trench, must be provided. A system of perforated pipe is placed in this permeable blanket and hence the water is allowed to flow by gravity from the trench. After the permeable material is placed, the trench can then be backfilled with ordinary roadway excavation and the embankment constructed across the area. These trenches involve fairly large quantities of excavated material. Depths of 40 to 70 feet and lengths in excess of two hundred feet are not unusual. Generally the material can be handled at prices that are little or none above the ordinary prices for roadway excavation. We have had several cases of stabilization trenches that involved tens of thousands of yards of excavated material and in some cases several hundred thousand yards of excavated material. The

Fig. 19 - Photo of stabilization trench under construction.

Fig. 20 - Placing perforated pipe and filter material in stabilization trench.

trenches result in two primary benefits. First, they remove much of the poor quality material that contributes to the original landslide. This material is placed with drier well compacted material. Secondly, the provision for a permeable blanket and a system of pipes to remove the groundwater provides a means of draining the subsurface water which in many cases is the primary cause of the trouble. This drainage will prevent the replaced material from becoming saturated and will slowly remove water from the area surrounding the trench where the poor quality material has been left in place. Our experience with this type of corrective measure has been quite satisfactory. Most cases where the operation has not been successful the failure has been due to the fact that the trench was not carried to sufficient depth to key into the better quality material below or where the slide material has been of such poor quality that it was impossible to construct a trench without a slide occurring in the side of trench. Caution is necessary in regard to the depth of the trench. The tendency will exist to bottom in the first firm material that is encountered as the trench is excavated. This in reality may be a firm layer that is underlain by the material that is the cause of the landslide. Exploratory steps should be taken to be sure of actual conditions.

Another method of landslide correction commonly used by The California Division of Highways has been the installation of horizontal drains (Fig. 21). The origin of horizontal drains is somewhat obscure. However the Division of Highways pioneered in their extensive use in the mid 1930's. Since that time many

Fig. 21 - Subsurface drainage of landslide by installing horizontal drains.

landslides have been corrected by the installation of horizontal drains. Initially, the installation of such drains was largely specialized work. In more recent years as better and more comprehensive drilling equipment has become available, it has become common practice to specify horizontal drains in landslide prevention and correction in normal highway construction. Extensive installations have been made not only in California but throughout many other parts of the world. In our experience, more than a hundred thousand lineal feet of horizontal drains are installed annually either as preventive or corrective measures. Simply, a horizontal drain consists of drilling a nearly horizontal hole from one to three hundred feet or more into a cut slope or into a foundation underlying an embankment area. These drains are drilled with modern power equipped machinery. After the drilling is completed, a perforated metal pipe, in our case, ordinary two-inch pipe that has been perforated and asphalt dipped, is placed in these holes. Usually a collector system is connected to the lower end of the horizontal drains. Water flows from these drains by gravity. The sole purpose of the horizontal drains is to remove groundwater from the area of instability.

The effectiveness of these drains is dependent upon the ability to intercept aquifers, fissures, zones or cracks that are carrying water. It should be pointed out that many materials that would normally be considered impervious are actually water bearing and can be effectively drained with horizontal drains. The water may be carried in joints, fissures or minute layers and large quantities of water can be removed by the use of horizontal drains. Horizontal drains are more extensively used for landslide prevention than they are for correction. One of the difficulties in using horizontal drains for landslide correction is that if the correction is not successful the drains will actually be destroyed by further movement of the landslide. Hence, it is frequently necessary in the correction of landslides to install horizontal drains on the flanks or from above the landslide in order to intercept the groundwater that is the cause of the problem. Once sufficient drains have been installed, to retard or stop the movement it is then possible to install horizontal drains through the actual landslide. They tend to remove the hydrostatic pressure and improve the strength of the slide material. While they are not a cure-all for landslides, or even for landslides that are caused by subsurface water, we have used them extensively and find that they are an effective means of landslide repair and far more economical than most or many other corrective measures.

Other methods of landslide correction involving subsurface drainage would include the installation of drainage galleries, tunnels, vertical wells and other somewhat specialized means. Drainage galleries or tunnels were far more common in application a decade or more ago but rising costs for this type of installation and the development of other more effective means have resulted in a decrease of this type of installation. The use of a drainage gallery or tunnel must be predicated on fairly precise knowledge of the location of aquifers or seepage zones that can be intercepted. Water is generally removed from gallery or tunnels by gravity, however upon occasion pumps may be installed. The use of vertical wells is a more common procedure in landslide prevention than in landslide correction (Fig. 22). A series of vertical wells are drilled along a line at the toe of slope, one edge or the median of the roadway, or most commonly at the upper toe of an embankment. These wells are usually sufficiently deep to intercept one or more water bearing zones and are preferably bottomed in good quality material.

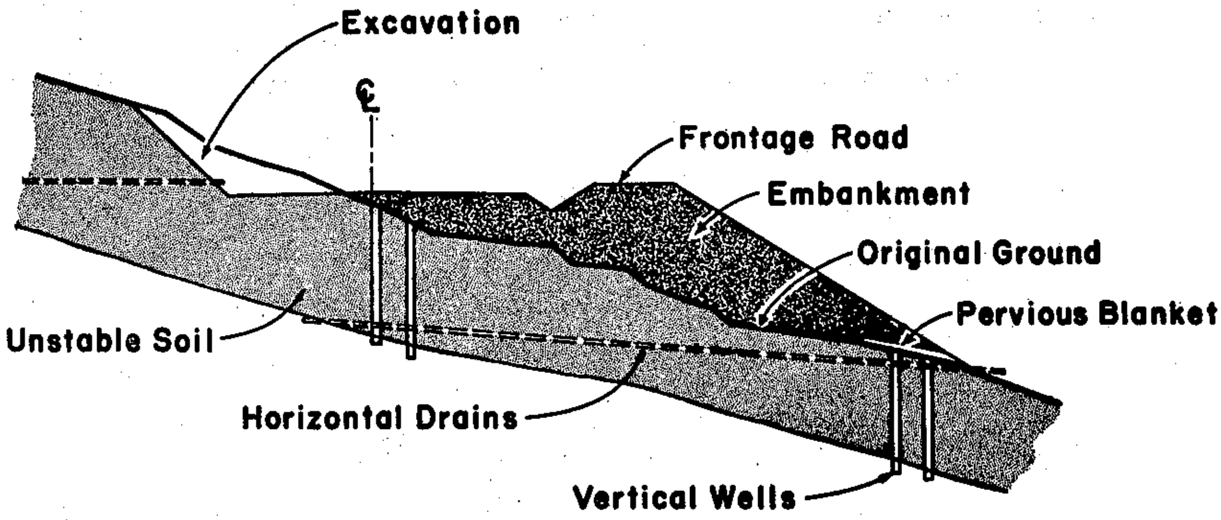


Fig. 22 - Illustration of slide treatment by use of vertical wells and horizontal drains.

Water is usually removed from the vertical wells by means of pumps, by horizontal drains or by connecting the bottoms of the wells with a tunnel and removing the water by gravity or by pumps. As is the case with horizontal drains, the success of this means of correction is dependent upon removal of ground-water and the resulting beneficial effects. Installations involving galleries, tunnels, or vertical wells are usually constructed at the head or near the head of a landslide or a potential landslide. These procedures would be of questionable value if installed within the slide mass since they would not necessarily rapidly improve conditions and their effectiveness would tend to be destroyed if further slide movement occurs.

Correction of landslides by means of subsurface drainage is widespread, however it is frequently combined with excavation measures or other procedures. If an actual landslide has occurred and damage to an existing facility has occurred, it will usually be necessary to make repairs to the engineering facilities in addition to providing subsurface drainage facilities. These repairs might consist of reconstruction within the slide mass or some other type of construction.

Restraining Structures

It is frequently possible to repair landslides by the construction of some type of restraining structure. These restraining structures might consist of buttresses of soil or rock, bin walls, retaining walls or other similar facilities. They have greatest application in landslides that are fairly small in magnitude or that consist predominantly of rock fall or movement of unsaturated material. The forces involved in the case of large mass movement of saturated soils are usually such that restraining structures may be of dubious or uncertain value. An exception would be the use of a buttress if it is practical both from the standpoint of size and of topography to construct a buttress of sufficient magnitude to resist the forces causing the slide movement.

Retaining structures are frequently used as a means of reconstruction in connection with an existing landslide. That is, other means such as excavation or surface drainage may be used to correct the landslide and restraining structures of some type used as a means of reconstructing the engineering facility in the desired location (Fig. 14).

Other means of repair of landslides that might be considered in the category of restraining structures would be the use of dowels, tie rods or rock bolting, piling, or miscellaneous measures such as grouting, and electro-osmosis. Rock bolting, tie rods or dowels are used principally on slides consisting of rock falls. They may be quite effective if conditions for their use is appropriate. Piling has been used with varying degrees of success. These probably have greater chance of success when the slide mass retains a major portion of its initial strength. Chemical grouting, electro-osmosis and freezing are processes that are quite specialized and usually are not warranted except in small areas or in cases where the facility to be protected is very expensive.

There are, upon occasions, situations where it is impractical economically to repair a landslide and yet it may be essential that a highway, railroad or other facility cross the existing landslide. Thus it may be necessary to construct or reconstruct engineering facilities in the area, assume the necessary risks involved and make the necessary future repairs or reconstruction to the engineering facility as the need arises. There are numerous highways at locations in California where we do not feel that we can at a reasonable cost correct an existing landslide (Fig. 23). In similar locations these highways will be or have been reconstructed to higher standards without correcting the landslide. Periodic patching, realignment or more drastic reconstruction measures are necessary and we accept this expense in lieu of attempting the more extensive repairs of the landslide.

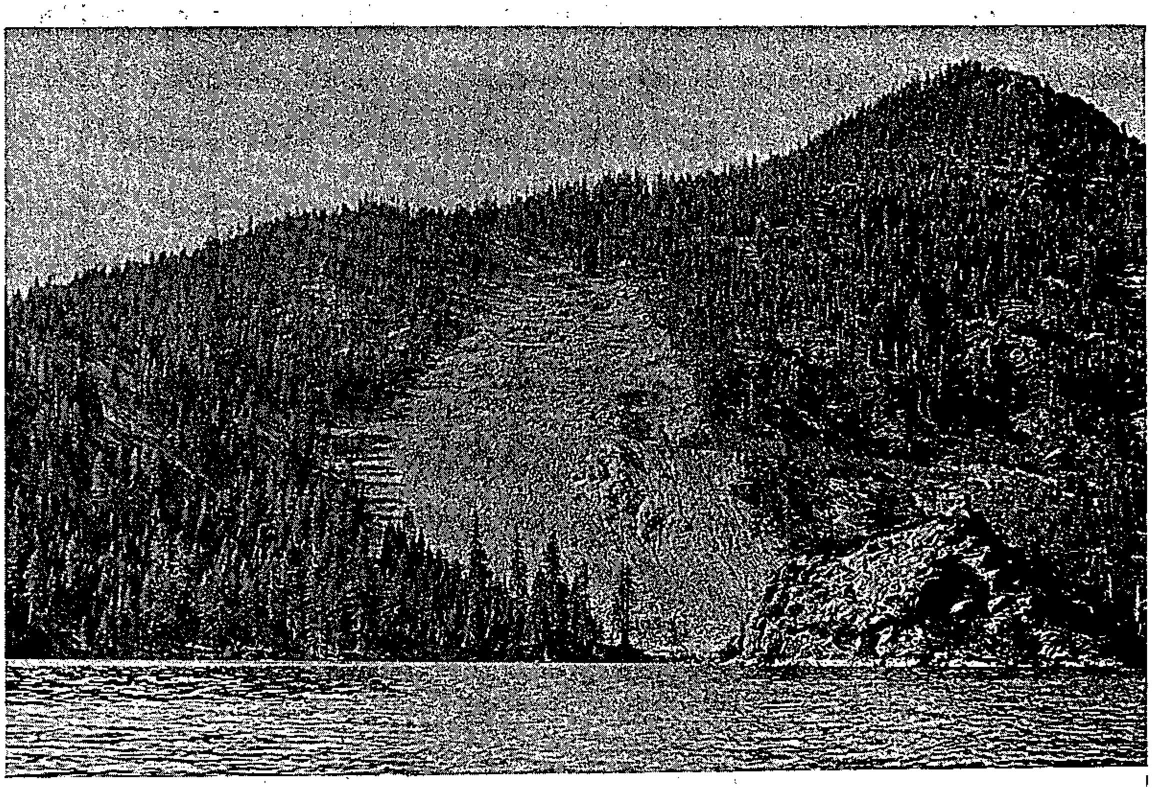


Fig. 23 - Well known Lake Tahoe Emerald Bay Slide.

Conclusions

In summary, the occurrence of a landslide is not necessarily cause for despair. Landslides can be corrected or repaired. Their repair will require competence in investigation, and analysis of conditions and factors affecting the repair. There is no rule of thumb method for selection of the type of repair to be used. In fact, with most landslides, there is seldom one and only one correct method for treatment. Most frequently more than one method of correction would be available and the actual selection will entail the evaluation of the various factors involved. Very frequently combinations of corrective methods are used. Correction or repair of landslides must be practical. Repair of a landslide that is based on adequate investigation, properly planned, and adequate as to correction but not practical to construct is of little or no value. This is not to discourage ingenuity and imagination in approaching landslide problems.

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